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RESEARCH ARTICLE

Comparison of Liquefaction Potential Analysis Methods Based on CPTu data on Reclamation Island, Pantai Indah Kapuk, DKI Jakarta, Indonesia

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Abstract

Liquefaction analysis in reclaimed areas has been intensively conducted because reclamation materials are generally non-cohesive and susceptible to liquefaction. Indonesia, known as the "Ring of Fire," has high seismic potential that can trigger liquefaction. The cone penetration test (CPT) is one of the methods used to obtain subsurface soil layer data, which are subsequently applied for liquefaction analysis and evaluation of the geological conditions of the study area. This study compares three currently developing methods for liquefaction analysis.

The results of soil layer analysis in the study area indicate three variations of sediment types, namely sand, silt, and clay. The method proposed by Boulanger and Idriss (2014) yields FS values < 1 for materials with fines content (FC) greater than 30%, which are considered susceptible to liquefaction. In contrast, the Robertson (2009) method also produces FS values < 1 for materials with FC > 30%, while the method proposed by Moss et al. (2006) results in FS values > 1 for materials with FC < 30%. The comparison of the three methods generally shows that the study area has a high liquefaction potential in clean sand materials at depths ranging from 4.5 to 15 m below the ground surface.

Keywords: Liquefaction analysis, factor of safety, cyclic stress ratio, sand, cone penetration test, CPTu.

1. Introduction

Liquefaction is a phenomenon in which soil strength is lost due to earthquake-induced vibrations in loose sandy soils. Soils that are potentially susceptible to liquefaction generally consist of granular materials ranging in particle size from sand to silt (Aydan et al., 2008). During an earthquake, the soil behaves more like a fluid than a solid, resulting in liquefaction that can trigger lateral spreading and ground settlement. One type of earthquake that frequently induces liquefaction is tectonic earthquakes caused by plate movements. Iwasaki (1982) stated that soils located at depths greater than 20 meters are not considered to have the potential to induce liquefaction

The large number of studies on liquefaction has encouraged the development of various methods for analyzing liquefaction potential in a given area. Several previous researchers have formulated equations to evaluate liquefaction potential and susceptibility. These studies attempt to relate liquefaction potential to soil characteristics and properties, while others associate it with the intensity of earthquake magnitude. Damage caused by an earthquake occurs when the earthquake force exceeds the threshold of the strain that is formed (Manan et al., 2023). This unpredictability in stratification and classification may result in unanticipated site circumstances during construction (Munirwansyah et al., 2020).

The study area is a reclaimed coastal zone that is planned to be developed as a residential area. This a shallow water area with an average depth of 15 meters (Aprilia and Pratomo, 2017). In addition, the groundwater table is relatively shallow, ranging from approximately 4 to 10 m below the ground surface. Given the possibility of future earthquakes in the study area, it is necessary to investigate liquefaction susceptibility using several methods to obtain more detailed and specific results through method comparison.

The Cone Penetration Test (CPT) is a method used to determine the geotechnical properties of sediments and to characterize sediment stratigraphy (Lunne et al., 1997). CPT is one of the primary tools widely used in geotechnical site investigations (Bell, 2007). Due to constraints in budget, time, or availability of subsurface soils, the soil profile information obtained from site investigation (e.g., boreholes, cone penetration test) is frequently limited, posing a significant challenge in interpreting the site investigation data and significant uncertainty in inferred soil stratification and classification at the site of interest (Hu and Wang, 2020). The lithological associations represented in each CPTu curve pattern reflect the distribution of facies at the study site (Styllas, 2014). CPT data is frequently directly employed in the construction of deepand shallowfoundations, as well as a range of other purposes (Munirwan et al., 2025).

The study area is located on one of the reclaimed islands in Pantai Indah Kapuk, North Jakarta, DKI Jakarta Province. Geographically, it is bounded by longitudes 106°44′47.86″E to 106°45′37.40″E and latitudes 6°5′27.55″S to

6°4′32.03″S. Administratively, the study area is bordered to the north and east by Jakarta Bay, to the west by Benda District, Tangerang City, and to the south by Penjaringan District, North Jakarta (Figure 1).

Fig. 1. Location of the study area (accessed via https://earth.google.com on 8 March 2023)

The Quaternary deposits in the DKI Jakarta area are part of the Ciputat Sub-Basin (Padmosukismo and Yahya, 1974), underlain by Tertiary rocks. This sub-basin is bounded by the Tangerang High to the west and the Rengasdengklok High to the east. The boundaries of these basin highs are inferred to be controlled by fault structures. The basin thickens eastward toward East Pasir and thins again in the Pamanukan–Jatibarang area (Figure 2).

The regional stratigraphy of the DKI Jakarta area according to Turkandi et al. (1992), The northern part of DKI Jakarta is dominated by Alluvial Deposits Unit (Qa). The alluvial deposits constitute the most extensive unit occupying the Jakarta Plain. This unit consists of clay-, silt-, sand-, and gravel- to pebble-sized materials derived from the weathering and reworking of older rocks, deposited by surface water flow or river processes. The distribution of this unit is mainly in the northern part of the DKI Jakarta area and extends in a west–east direction from Kalideres, Cengkareng, Grogol, Petamburan, Gambir, Cempaka Putih, Kelapa Gading, and continues eastward. This unit is closely associated with coastal plain morphology. Within this unit, ancient river deposits are also present, representing paleochannel systems. These deposits occupy the southern, western, and eastern parts of the Jakarta Plain. The sediments are reworked products of older rocks, consisting of fine to coarse sand, black in color, loosely consolidated, and distributed along former river channels or nearly perpendicular to the coastline, with a generally south–north orientation.

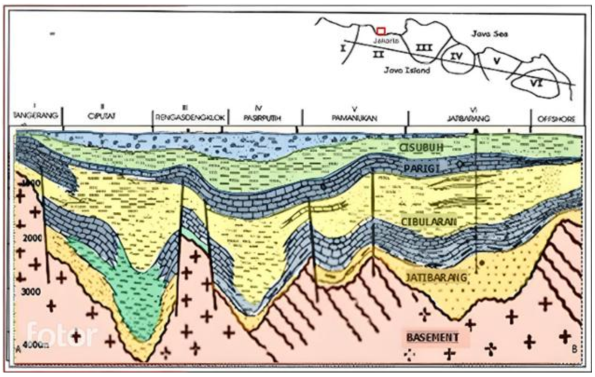

Fig. 2. West–East cross section of the North West Java Basin (Padmosukismo and Yahya, 1974).

Physiographically, the waters of Jakarta Bay are part of the Ciputat Basin. This basin functions as the depositional basin of Jakarta Bay and is bounded by the Tinggian Tangerang to the west, the Tinggian Rengasdengklok to the east, and the Seribu Islands to the north. Therefore, the boundaries of the Ciputat Basin are inferred to be tectonic in nature. The Pliocene–Pleistocene tectonic phase, which formed reverse faults along the southern zone and normal faults in the northern part of the North West Java Basin, accompanied by volcanic activity, played an important role in the sedimentation processes of the Quaternary deposits within the Ciputat Basin (Rimbaman, 1992; Gafoer and Samodra, 1993). The characteristics of Quaternary sediments in the Jakarta Bay area reflect depositional processes occurring from the early Pleistocene to the present. The stratigraphic position and characteristics of the Quaternary sediments in Jakarta Bay are strongly influenced by global sea-level fluctuations of the Sunda Shelf (Triapriyasen et al., 2016).

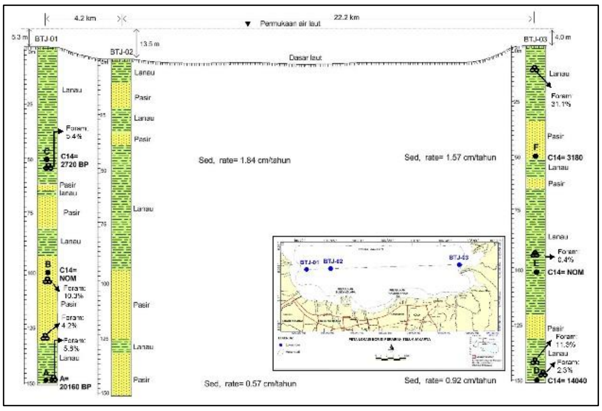

Fig. 3. Sediment layers of Jakarta Bay based on borehole data (Darlan et al., 2020).

The general water circulation pattern in the western part of Jakarta Bay moves toward the southeast, entering the bay basin area (Triapriyasen et al., 2016). Grain-size analysis indicates that two dominant sediment fractions are present in Jakarta Bay waters, namely sand and sandy silt (Triapriyasen et al., 2016). Based on core drilling results shown in Figure 3, the sedimentation cycle begins with the lowermost core sediments composed of silt deposited in a calm water environment, followed by a transition from calm to more dynamic depositional conditions characterized by sand deposits. The sedimentation cycle ends with the uppermost core sediments consisting of silt deposited in a calm water environment (Darlan et al., 2020).

2. Data and Methods

The data used in this study consist of CPTu data from 10 locations with depths ranging from 13.15 to 17.65 m, as well as secondary data in the form of regional seismic information. The CPTu data include three parameters: (1) cone resistance (qc), (2) sleeve friction (fs), and (3) pore pressure (u2).

This study employs three different methods to analyze liquefaction potential, namely those proposed by Robertson (2009), Moss et al. (2006), and Boulanger and Idriss (2014), using the CLiq software.

The CPTu data from the 10 locations, with depths varying from 13.15 to 17.65 m, are used together with seismic data from the study area. To determine the friction ratio (F) and the corrected cone resistance (Q) with respect to vertical overburden stress, the following equations are applied proposed by Robertson and Wride (1998):

$$F = [f_s / (q_c - \sigma_{v0})] \times 100\% \quad \text{.................................} \quad (1)$$

$$Q = (q_c - \sigma_{v0}) / \sigma'_{v0} \quad \text{...} \quad (2)$$

where σ_{v0} is the total vertical stress and σ'_{v0} is the effective vertical stress.

Table 1. Groundwater level and coordinates of the locations

CPTu No.	Easting	Northing	Elev. (mSL)	GWL (mSL)
CH1750	693354.81	9327366.76	5.49	-1.15
CH1850	693419.05	9327442.80	5.92	-0.70
CH2450	693723.56	9327962.16	6.80	-2.27
CH2550	693761.20	9328059.45	6.85	-2.13
CH2650	694152.48	9326883.08	5.43	-1.07
CH3600	694494.07	9327862.20	6.34	-0.59
CH3750	694494.71	9327726.34	6.04	-1.70
CH3850	694420.93	9327636.55	6.03	-0.56
CH4950	694057.75	9326598.69	5.50	-1.08
CH5050	694023.45	9326499.19	5.70	-0.54

Liquefaction potential analysis is carried out by calculating liquefaction parameters using peak ground acceleration (PGA). The PGA value is obtained from the 2017 Indonesian Seismic Hazard Map (Irsyam et al., 2017), taking into account the site coefficient (FPGA) in determining peak ground acceleration from the earthquake source. CPTu data are then used to compute the cyclic stress ratio (CSR), cyclic resistance ratio (CRR), liquefaction safety factor (FS).

In determining the factor of safety, Robertson (2009), Boulanger and Idriss (2014), and Moss et al. (2006) use Equation as follows:

$$FS = CRR / CSR \quad \text{...} \quad (3)$$

After obtaining the FS value, the level of liquefaction potential is determined using the factor of safety criteria proposed by Juang et al. (2008), as presented in Table 1 below:

Table 2. Factor of Safety for Liquefaction (Juang et al., 2008)

FS < 1	Potential for liquefaction
FS = 1	Critical condition
FS > 1	Not susceptible to liquefaction

3. Result

Peak Ground Acceleration (PGA) were performed using an earthquake scenario with a magnitude of Mw 6.7 originating from the Cimandiri Fault. This fault is a major fault system in West Java, forming a scarp approximately 100 km long trending northeast–southwest from Padalarang to Pelabuhan Ratu, with a slip rate of about 0.55 mm/year (PuSGeN, 2017).

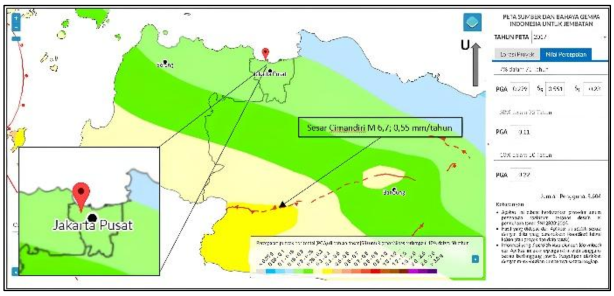

Fig. 4. Map of maximum bedrock acceleration for a 10% probability of exceedance in 50 years (Pusat Studi Gempa Nasional, 2017).

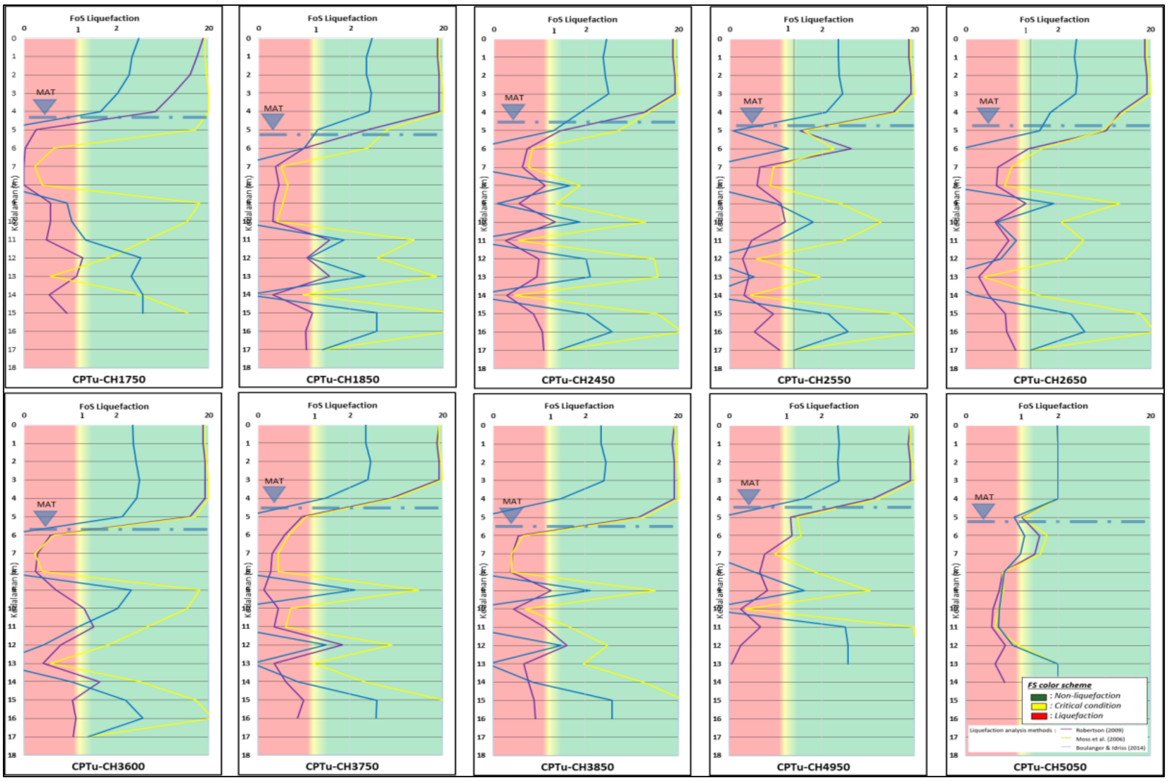

Fig. 5. Graph of liquefaction analysis results with respect to depth at each CPTu location.

In general, the liquefaction safety factor (FS) results obtained using the three different methods show nearly similar outcomes (see Table 3), indicating an average liquefaction potential at depths ranging from 4.5 to 15 m below the ground surface. This is evidenced by CSR values that are greater than the corresponding CRR values. The cross sections of the factor of safety (FS) for each profile can be seen in Figure 6 for cross section A–A′, Figure 7 for cross section B–B′, Figure 8 for cross section C–C′, and Figure 9 for cross section D–D′.

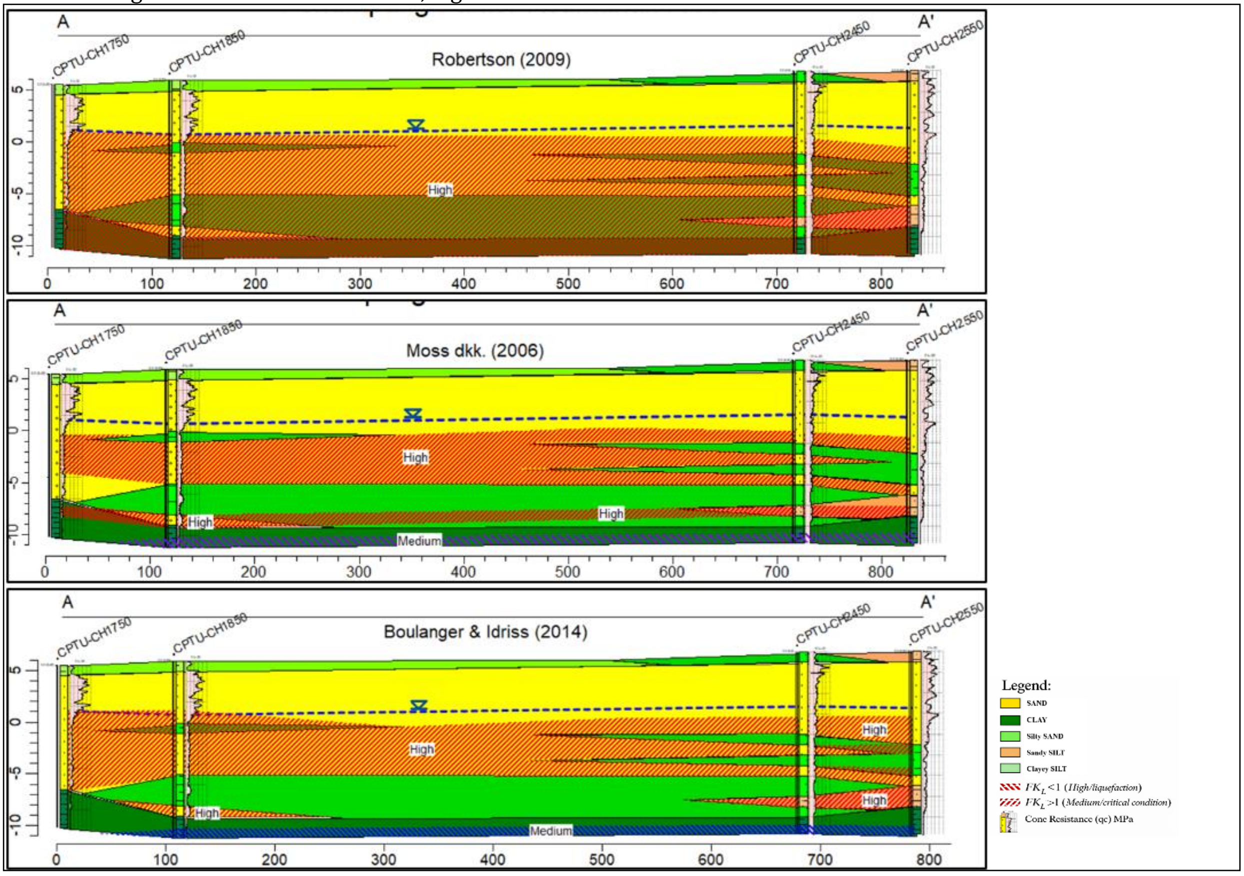

Fig. 6. Factor of safety cross section A–A′.

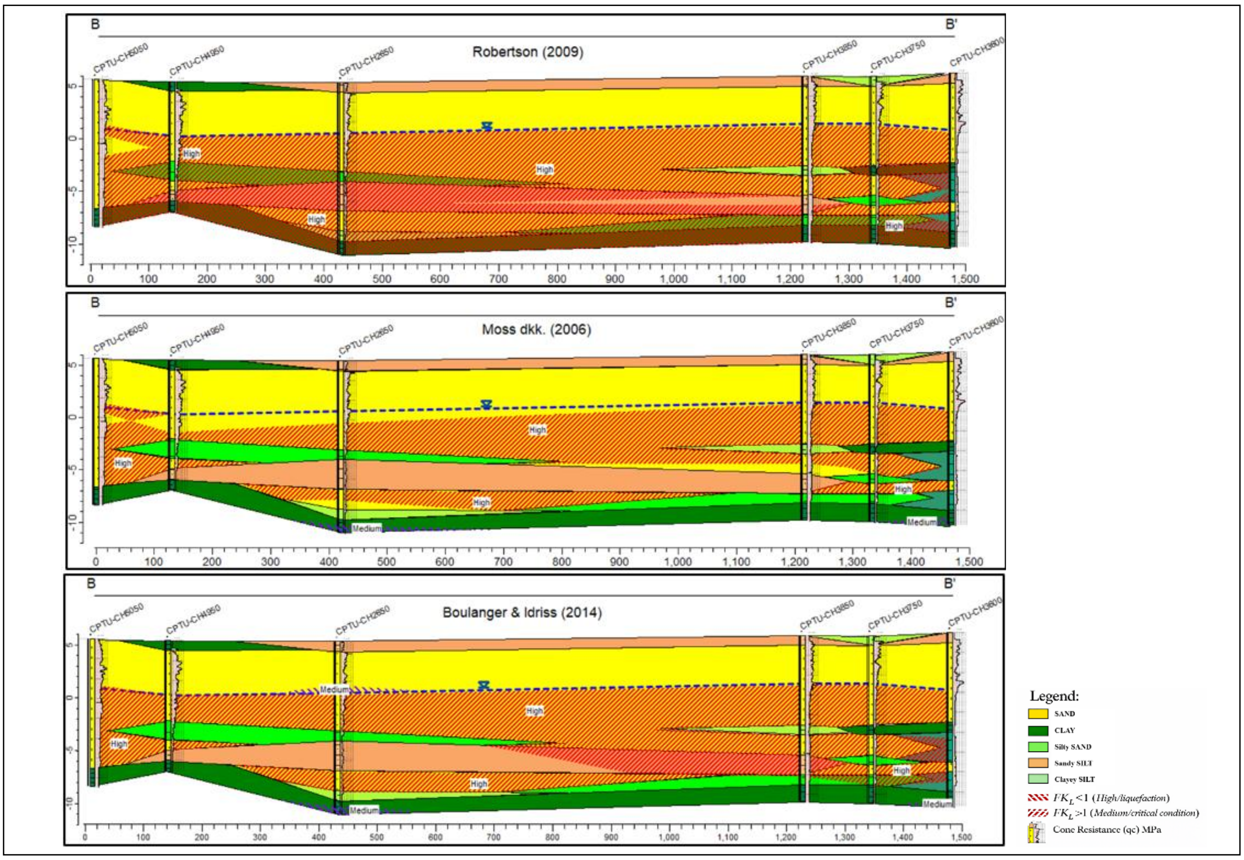

Fig. 7. Factor of safety cross section B–B′.

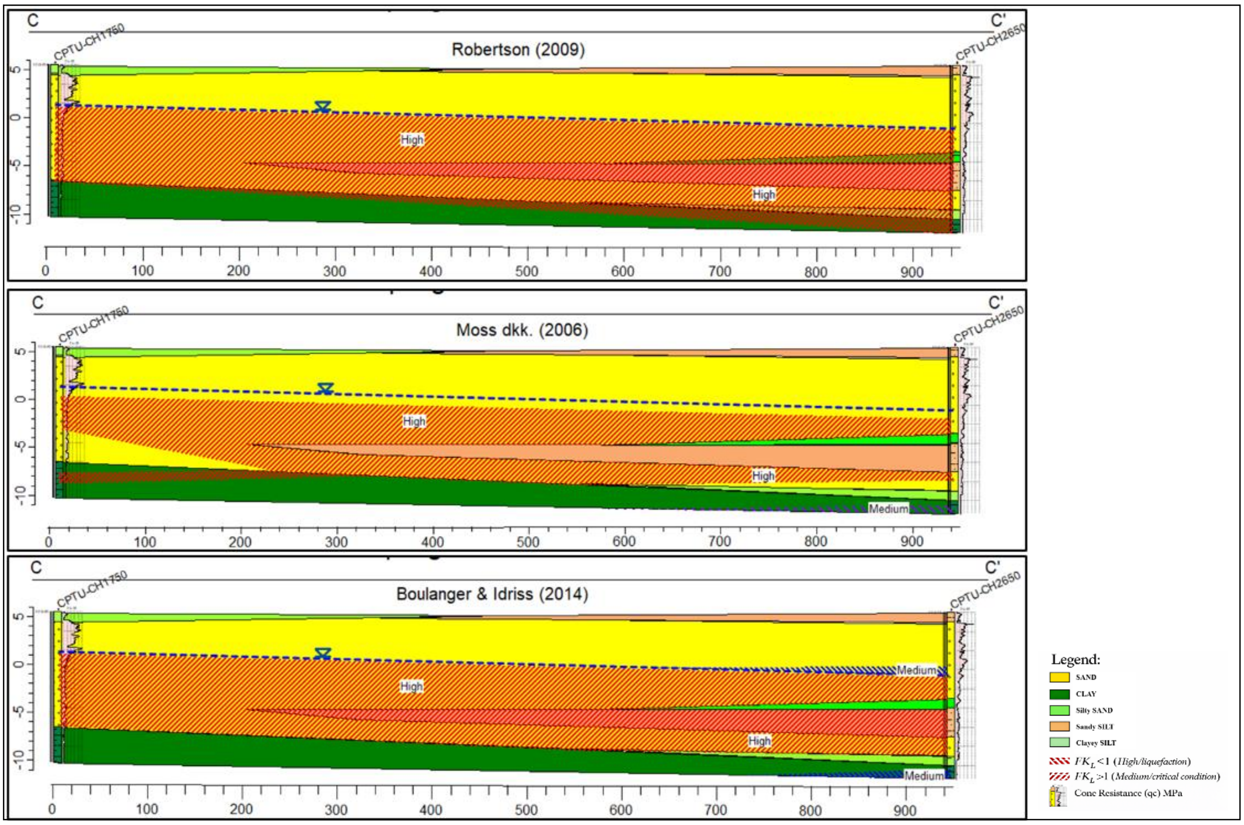

Fig. 8. Factor of safety cross section C–C′.

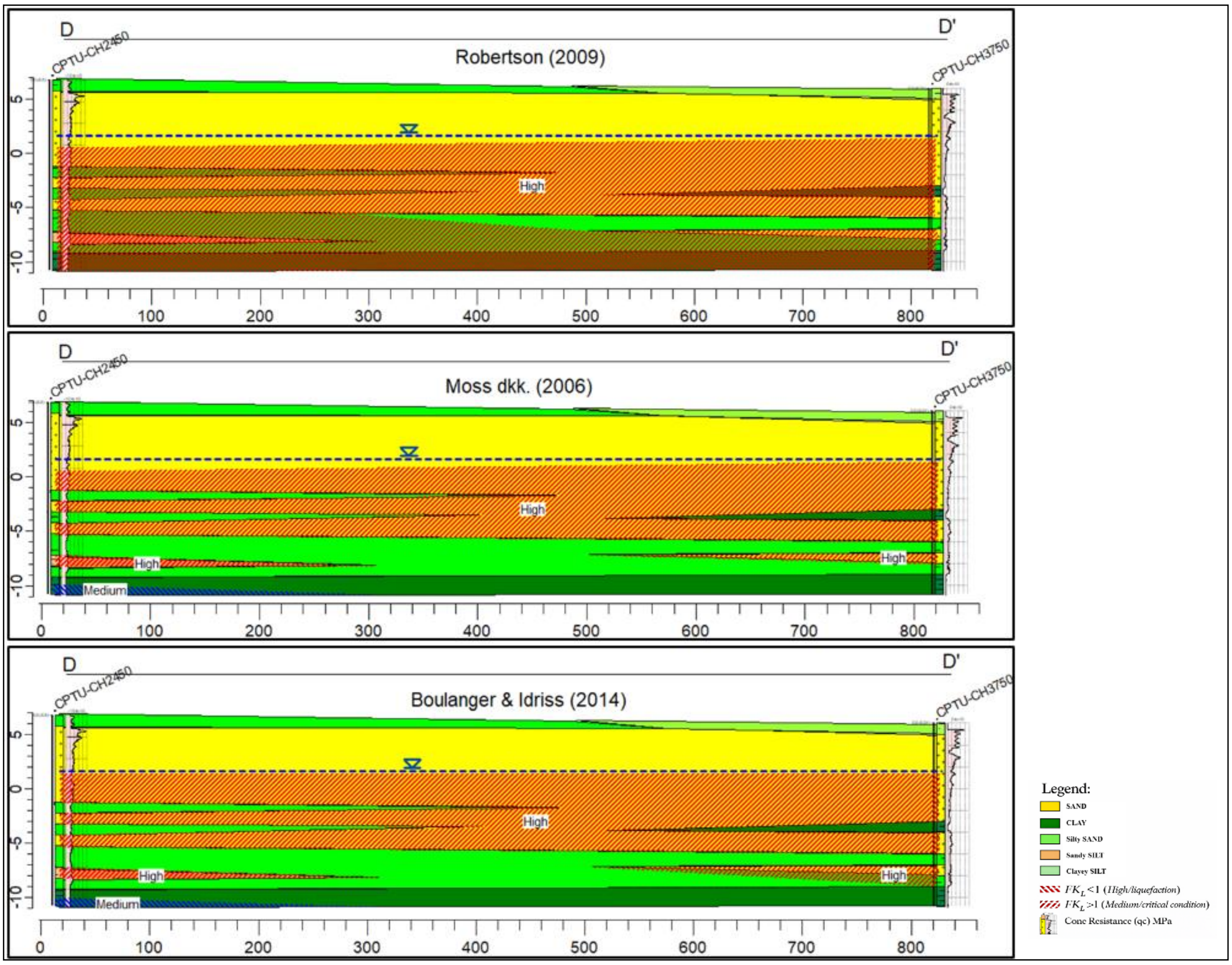

Fig. 9. Factor of safety cross section D–D′.

Table 3. Results of the comparison of liquefaction analysis using three different methods: Robertson (2009)[1*], Moss et al. (2006)[2*], and Boulanger & Idriss (2014)[3*].

CPTu ID	Depth (m)		Soil Type	Tip Resistance (qc MPa)	FC (%)	CSR			CRR			FS		
	From	To				1*	2*	3*	1*	2*	3*	1*	2*	3*
CPTu-CH1750	0	1	Clayey SILT	1 - 15	28.06	0.23	0.22	1.15	4.00	4.00	4.00	17.39	18.18	3.48
	1	2			4.05	0.27	0.22	1.35	4.00	4.00	4.00	14.81	18.18	2.96
	2	3		2 - 28	3.18	0.32	0.21	1.35	4.00	4.00	3.74	12.50	19.05	2.77
	3	4			3.56	0.35	0.20	1.30	2.93	4.00	2.70	8.37	20.00	2.08
	4	5			8.98	0.36	0.20	1.22	1.91	4.00	1.64	5.31	20.00	1.34
	5	6			9.63	0.37	0.19	1.05	0.10	2.74	0.11	0.27	14.42	0.10
	6	7	SAND		9.73	0.39	0.19	1.05	0.08	0.08	0.11	0.21	0.42	0.10
	7	8			6.51	0.40	0.19	1.04	0.08	0.05	0.11	0.20	0.26	0.11
	8	9		2 - 5	5.58	0.40	0.19	1.04	0.08	0.06	0.11	0.20	0.32	0.11
	9	10			13.55	0.41	0.19	1.04	0.16	3.01	0.61	0.39	15.84	0.59
	10	11			14.36	0.41	0.18	1.05	0.16	2.11	0.69	0.39	11.72	0.66
	11	12			23.20	0.40	0.18	1.05	0.14	0.77	0.97	0.35	4.28	0.92
	12	13			61.62	0.39	0.18	1.04	0.34	0.30	3.81	0.87	1.67	3.66
	13	14	CLAY	0,5 - 3	50.35	0.38	0.18	1.04	0.28	0.07	3.03	0.74	0.39	2.91
	14	15			78.34	0.37	0.18	1.04	0.14	0.66	4.00	0.38	3.67	3.85
	15	16			76.31	0.36	0.18	1.04	0.21	2.14	4.00	0.58	11.89	3.85
CPTu-CH1850	0	1	Clayey SILT	1 - 20	25.44	0.23	0.22	1.18	4.00	4.00	4.00	17.39	18.18	3.39
	1	2			6.09	0.23	0.22	1.35	4.00	4.00	4.00	17.39	18.18	2.96
	2	3			3.13	0.22	0.21	1.35	4.00	4.00	4.00	18.18	19.05	2.96
	3	4	SAND	1 - 27	7.52	0.22	0.20	1.20	4.00	4.00	4.00	18.18	20.00	3.33
	4	5			6.98	0.22	0.20	1.25	4.00	4.00	4.00	18.18	20.00	3.20
	5	6			12.53	0.23	0.19	1.07	0.70	0.94	0.94	3.04	4.95	0.88
	6	7	Sandy SILT		14.83	0.24	0.20	1.05	0.15	0.61	0.66	0.63	3.05	0.63
	7	8			5.93	0.26	0.20	1.05	0.08	0.07	0.11	0.31	0.35	0.10
	8	9	SAND	2 - 6	5.00	0.27	0.19	1.04	0.09	0.08	0.11	0.33	0.42	0.11
	9	10			5.00	0.27	0.19	1.05	0.08	0.07	0.11	0.30	0.37	0.10
	10	11			7.97	0.28	0.19	1.05	0.08	0.06	0.12	0.29	0.32	0.11
	11	12			29.13	0.28	0.18	1.06	0.33	1.76	1.79	1.18	9.78	1.69
	12	13	Sandy SILT	0,8 - 7,5	15.11	0.28	0.18	1.05	0.19	0.70	0.75	0.68	3.89	0.71
	13	14			47.40	0.28	0.18	1.05	0.33	3.01	3.03	1.18	16.72	2.89
	14	15	SAND	0,75 - 3,5	8.68	0.28	0.18	1.05	0.08	0.11	0.16	0.29	0.61	0.15
	15	16			83.92	0.27	0.17	1.04	0.21	4.00	4.00	0.78	23.53	3.85
	16	17	CLAY	0,5 - 1,4	90.79	0.26	0.17	1.04	0.17	4.00	4.00	0.65	23.53	3.85
	17	18			93.03	0.24	0.16	0.16	0.16	0.16	0.16	0.67	1.00	1.00
CPTu-CH2450	0	1	Sandy SILT	1,7 - 10,5	24.47	0.23	0.22	1.20	4.00	4.00	4.00	17.39	18.18	3.33
	1	2			10.22	0.23	0.22	1.30	4.00	4.00	4.00	17.39	18.18	3.08
	2	3		< 38	6.87	0.22	0.21	1.24	4.00	4.00	4.00	18.18	19.05	3.23
	3	4			15.02	0.22	0.20	1.14	4.00	4.00	4.00	18.18	20.00	3.51
	4	5	SAND		8.91	0.22	0.20	1.07	1.87	1.87	1.87	8.50	9.35	1.75
	5	6		.	23.12	0.24	0.20	1.06	0.25	0.91	0.94	1.04	4.55	0.89
	6	7		1,4 - 10	9.64	0.26	0.21	1.06	0.12	0.11	0.12	0.46	0.52	0.11
	7	8			6.06	0.27	0.21	1.05	0.11	0.10	0.11	0.41	0.48	0.10
	8	9	Sandy SILT	2,6 - 6	29.69	0.28	0.21	1.05	0.20	0.36	1.39	0.71	1.71	1.32
	9	10	SAND	0,6 - 5,6	16.98	0.29	0.20	1.05	0.11	0.19	0.23	0.38	0.95	0.22
	10	11	Sandy SILT	2,8 - 6	35.59	0.29	0.20	1.05	0.27	1.76	1.79	0.93	8.80	1.70
	11	12	SAND		7.91	0.30	0.19	1.04	0.08	0.07	0.11	0.27	0.37	0.11
	12	13	Sandy SILT	0,5 - 5,5	44.96	0.29	0.19	1.04	0.18	2.07	2.09	0.62	10.89	2.01
	13	14			48.88	0.29	0.19	1.04	0.17	2.26	2.29	0.59	11.89	2.20
	14	15	Silty SAND		7.09	0.29	0.18	1.04	0.08	0.06	0.11	0.28	0.33	0.11
	15	16	Sandy SILT	< 0,58	42.26	0.28	0.18	1.04	0.15	2.11	2.13	0.54	11.72	2.05
	16	17	CLAY	< 0,85	84.83	0.27	0.18	1.04	0.18	4.00	4.00	0.67	22.22	3.85
	17	18			86.87	0.26	0.18	0.18	0.18	0.18	0.18	0.69	1.00	1.00
CPTu-CH2550	0	1	Silty SAND	3 - 22,5	17.12	0.23	0.22	1.32	4.00	4.00	4.00	17.39	18.18	3.03
	1	2			8.46	0.23	0.22	1.34	4.00	4.00	4.00	17.39	18.18	2.99
	2	3			9.04	0.22	0.21	1.30	4.00	4.00	4.00	18.18	19.05	3.08
	3	4		4 - 23	6.82	0.22	0.20	1.21	4.00	4.00	4.00	18.18	20.00	3.31
	4	5	SAND		5.38	0.22	0.20	1.18	2.59	2.59	2.60	11.77	12.95	2.20
	5	6			7.49	0.24	0.20	1.11	0.28	0.25	0.24	1.17	1.25	0.22
	6	7		.	3.55	0.25	0.20	1.17	1.04	0.53	1.01	4.16	2.65	0.86
	7	8		4 - 10	5.00	0.27	0.20	1.05	0.11	0.12	0.11	0.43	0.60	0.10
	8	9			6.05	0.28	0.20	1.05	0.11	0.11	0.11	0.39	0.55	0.10
	9	10			18.16	0.28	0.20	1.06	0.20	0.63	0.67	0.71	3.15	0.63
	10	11	Sandy SILT	0,5 - 6	32.43	0.29	0.19	1.05	0.23	1.64	1.67	0.79	8.63	1.59
	11	12			15.11	0.29	0.19	1.05	0.10	0.65	0.69	0.34	3.42	0.66
	12	13	SAND	2,7 - 6	7.12	0.29	0.18	1.05	0.08	0.07	0.11	0.28	0.39	0.10
	13	14	Silty SAND	0,6 - 5,6	13.66	0.28	0.18	1.05	0.09	0.34	0.39	0.32	1.89	0.37
	14	15			5.00	0.28	0.18	1.05	0.08	0.06	0.11	0.29	0.33	0.10
	15	16			54.16	0.27	0.18	1.04	0.16	2.38	2.41	0.59	13.22	2.32
	16	17	CLAY	< 0,65	99.98	0.27	0.18	1.04	0.10	4.00	4.00	0.37	22.22	3.85
	17	18			100.00	0.26	0.18	0.18	0.18	0.18	0.18	0.69	1.00	1.00
CPTu-CH2650	0	1	Silty SAND	1,5 - 12	22.06	0.23	0.22	1.28	4.00	4.00	4.00	17.39	18.18	3.13
	1	2			7.86	0.23	0.22	1.34	4.00	4.00	4.00	17.39	18.18	2.99
	2	3			5.43	0.22	0.21	1.26	4.00	4.00	4.00	18.18	19.05	3.17
	3	4		2- 44	5.14	0.22	0.20	1.29	4.00	4.00	4.00	18.18	20.00	3.10
	4	5	SAND		9.19	0.23	0.20	1.27	2.15	2.03	2.10	9.35	10.15	1.65
	5	6			3.50	0.25	0.21	1.28	1.64	1.27	1.60	6.56	6.05	1.25
	6	7			5.29	0.26	0.21	1.13	0.25	0.27	0.20	0.96	1.29	0.18
	7	8		3 - 10	5.80	0.27	0.21	1.05	0.12	0.13	0.12	0.44	0.62	0.11
	8	9			10.89	0.28	0.21	1.06	0.12	0.11	0.12	0.43	0.52	0.11
	9	10	Sandy SILT		40.44	0.29	0.20	1.05	0.26	1.83	1.87	0.90	9.15	1.78
	10	11			11.98	0.29	0.20	1.05	0.12	0.43	0.46	0.41	2.15	0.44
	11	12	Silty SAND	1,2 - 7,8	14.97	0.29	0.19	1.05	0.17	0.71	0.74	0.59	3.74	0.70
	12	13			11.45	0.29	0.19	1.05	0.12	0.46	0.50	0.41	2.42	0.48
	13	14	SAND	0,6 - 7	5.00	0.29	0.19	1.04	0.08	0.06	0.10	0.28	0.32	0.10
	14	15			8.47	0.28	0.18	1.04	0.10	0.22	0.26	0.36	1.22	0.25
	15	16	Clayey SILT		60.58	0.28	0.18	1.04	0.15	2.82	2.83	0.54	15.67	2.72
	16	17	CLAY	< 1	92.20	0.27	0.18	1.04	0.15	4.00	4.00	0.56	22.22	3.85
	17	18			95.95	0.26	0.18	0.18	0.18	0.18	0.18	0.69	1.00	1.00
CPTu-CH3600	0	1	Silty SAND	< 32	28.17	0.23	0.22	1.33	4.00	4.00	4.00	17.39	18.18	3.01
	1	2			5.71	0.23	0.22	1.32	4.00	4.00	4.00	17.39	18.18	3.03
	2	3			7.27	0.22	0.21	1.23	4.00	4.00	4.00	18.18	19.05	3.25
	3	4		< 23	15.11	0.22	0.20	1.13	4.00	4.00	4.00	18.18	20.00	3.54
	4	5			6.81	0.22	0.20	1.21	4.00	4.00	4.00	18.18	20.00	3.31
	5	6	SAND		4.40	0.22	0.19	1.18	2.74	2.74	2.73	12.45	14.42	2.31
	6	7			6.91	0.23	0.19	1.05	0.09	0.08	0.12	0.39	0.42	0.11
	7	8		2 – 8,7	6.36	0.25	0.19	1.05	0.07	0.05	0.11	0.28	0.26	0.10
	8	9			6.56	0.26	0.19	1.05	0.07	0.06	0.11	0.27	0.32	0.10
	9	10	CLAY	< 6	73.44	0.27	0.19	1.04	0.12	3.01	3.03	0.44	15.84	2.91
	10	11			54.55	0.27	0.18	1.04	0.24	2.11	2.13	0.89	11.72	2.05
	11	12	Silty CLAY	4 - 9	21.41	0.28	0.18	1.05	0.32	0.77	0.81	1.14	4.28	0.77
	12	13			10.91	0.28	0.18	1.04	0.14	0.30	0.34	0.50	1.67	0.33
	13	14	SAND	2 - 7	5.00	0.28	0.18	1.04	0.09	0.07	0.10	0.32	0.39	0.10
	14	15	Silty CLAY	< 7,5	18.61	0.27	0.18	1.05	0.36	0.66	0.69	1.33	3.67	0.66
	15	16			47.97	0.27	0.18	1.04	0.18	2.62	2.64	0.67	14.56	2.54
	16	17	CLAY	< 0,85	81.33	0.26	0.18	1.04	0.19	4.00	4.00	0.73	22.22	3.85
	17	18			83.66	0.25	0.17	0.17	0.17	0.17	0.17	0.68	1.00	1.00

Table 3. (Continued) Results of the comparison of liquefaction analysis using three different methods: Robertson (2009)[1*], Moss et al. (2006)[2*], and Boulanger & Idriss (2014)[3*].

CPTu ID	Depth (m) From	Depth (m) To	Soil Type	Tip Resistance (qc MPa)	FC (%)	CSR 1*	CSR 2*	CSR 3*	CRR 1*	CRR 2*	CRR 3*	FS 1*	FS 2*	FS 3*
CPTu-CH3750	0	1	Clayey SILT	< 32	39.90	0.22	0.22	1.35	4.00	4.00	4.00	18.18	18.18	2.96
	1	2	SAND	2 - 23	3.23	0.23	0.22	1.35	4.00	4.00	4.00	17.39	18.18	2.96
	2	3			11.81	0.22	0.21	1.20	4.00	4.00	4.00	18.18	19.05	3.33
	3	4			7.55	0.22	0.20	1.28	4.00	4.00	4.00	18.18	20.00	3.13
	4	5			11.02	0.23	0.20	1.14	1.27	1.22	1.22	5.52	6.10	1.07
	5	6		< 6,7	10.54	0.25	0.21	1.04	0.15	0.14	0.14	0.60	0.67	0.13
	6	7			5.62	0.26	0.21	1.04	0.10	0.09	0.11	0.38	0.43	0.11
	7	8			5.00	0.28	0.21	1.04	0.08	0.07	0.10	0.29	0.33	0.10
	8	9			5.00	0.29	0.21	1.04	0.08	0.07	0.11	0.28	0.33	0.11
	9	10	CLAY	< 6	58.15	0.30	0.21	1.04	0.07	2.31	2.33	0.23	11.00	2.24
	10	11	SAND	5 - 9	5.00	0.30	0.20	1.04	0.10	0.09	0.10	0.33	0.45	0.10
	11	12			4.95	0.30	0.20	1.04	0.09	0.08	0.10	0.30	0.40	0.10
	12	13	Sandy SILT	4 - 5,6	30.85	0.31	0.20	1.06	0.51	1.13	1.16	1.65	5.65	1.09
	13	14	SAND	2 - 7	7.73	0.30	0.19	1.04	0.09	0.15	0.18	0.30	0.79	0.17
	14	15	Sandy SILT	< 7,5	14.52	0.30	0.19	1.04	0.12	0.54	0.57	0.40	2.84	0.55
	15	16	CLAY	< 1	81.12	0.29	0.19	1.04	0.18	4.00	4.00	0.62	20.95	3.85
	16	17			94.64	0.28	0.19	1.03	0.15	3.95	3.95	0.54	20.79	3.83
CPTu-CH3850	0	1	Silty SAND	< 26	26.99	0.22	0.22	1.35	4.00	4.00	4.00	18.18	18.18	2.96
	1	2	SAND	8 - 33	6.03	0.23	0.21	1.35	4.00	4.00	4.00	17.39	19.05	2.96
	2	3			6.80	0.22	0.21	1.34	4.00	4.00	4.00	18.18	19.05	2.99
	3	4			5.85	0.22	0.20	1.32	4.00	4.00	4.00	18.18	20.00	3.03
	4	5			10.44	0.22	0.20	1.29	4.00	4.00	4.00	18.18	20.00	3.10
	5	6			11.80	0.22	0.19	1.18	1.65	1.64	1.64	7.50	8.63	1.39
	6	7		< 10	5.17	0.24	0.19	1.05	0.09	0.08	0.11	0.38	0.42	0.10
	7	8			5.00	0.25	0.19	1.05	0.08	0.06	0.11	0.32	0.32	0.10
	8	9			7.54	0.26	0.19	1.05	0.08	0.06	0.11	0.31	0.32	0.10
	9	10	Clayey SILT	< 4,7	40.19	0.27	0.19	1.05	0.23	2.15	2.17	0.85	11.32	2.07
	10	11	SAND	< 9,5	8.00	0.27	0.18	1.04	0.09	0.08	0.10	0.33	0.44	0.10
	11	12			5.92	0.28	0.18	1.05	0.20	0.24	0.22	0.71	1.33	0.21
	12	13	Silty SAND	1,75 - 7	18.79	0.28	0.18	1.06	0.35	0.62	0.66	1.25	3.44	0.62
	13	14			9.87	0.28	0.18	1.04	0.12	0.34	0.38	0.43	1.89	0.37
	14	15	Sandy SILT	< 5,7	34.79	0.27	0.18	1.04	0.13	1.56	1.58	0.48	8.67	1.52
	15	16	CLAY	< 0,9	86.43	0.27	0.17	1.04	0.15	4.00	4.00	0.56	23.53	3.85
	16	17			88.00	0.26	0.17	1.02	0.15	3.94	3.94	0.58	23.18	3.86
CPTu-CH4950	0	1	CLAY	< 15,8	54.65	0.22	0.22	1.35	4.00	4.00	4.00	18.18	18.18	2.96
	1	2	SAND	2.5 – 26.3	7.40	0.23	0.22	1.30	4.00	4.00	4.00	17.39	18.18	3.08
	2	3			4.00	0.22	0.21	1.34	4.00	4.00	4.00	18.18	19.05	2.99
	3	4			12.61	0.22	0.20	1.30	4.00	4.00	4.00	18.18	20.00	3.08
	4	5			6.41	0.23	0.20	1.21	1.65	1.69	1.55	7.17	8.45	1.28
	5	6		5 - 9,7	7.78	0.24	0.21	1.11	0.22	0.23	0.17	0.92	1.10	0.15
	6	7			4.88	0.24	0.21	1.11	0.23	0.25	0.18	0.96	1.19	0.16
	7	8			6.00	0.27	0.21	1.06	0.13	0.13	0.12	0.48	0.62	0.11
	8	9	Sandy SILT	< 6,5	13.53	0.28	0.21	1.05	0.12	0.36	0.39	0.43	1.71	0.37
	9	10			31.64	0.29	0.20	1.05	0.15	1.32	1.36	0.52	6.60	1.30
	10	11	SAND	3,3 - 4,2	5.00	0.30	0.20	1.04	0.08	0.06	0.11	0.27	0.30	0.11
	11	12	Silty SAND	< 3,2	89.97	0.30	0.19	1.04	0.13	3.76	3.77	0.43	19.79	3.63
	12	13	CLAY	< 0,55	99.45	0.30	0.19	1.04	0.08	4.00	4.00	0.27	21.05	3.85
	13	14			100.00	0.28	0.18	0.97	0.06	3.75	3.75	0.21	20.83	3.87
CPTu-CH5050	0	1	SAND	< 28	15.80	0.22	0.21	1.23	4.00	4.00	4.00	1.98	1.98	1.98
	1	2			5.06	0.23	0.22	1.31	4.00	4.00	4.00	2.00	2.00	2.00
	2	3			9.48	0.22	0.21	1.24	4.00	4.00	4.00	2.00	2.00	2.00
	3	4			8.10	0.22	0.20	1.31	4.00	4.00	4.00	2.00	2.00	2.00
	4	5			4.80	0.22	0.20	1.11	4.00	4.00	4.00	2.00	2.00	2.00
	5	6			5.97	0.23	0.19	1.05	0.43	0.43	0.43	0.81	0.85	0.68
	6	7		0,5 - 9,5	4.56	0.24	0.20	1.12	0.34	0.30	0.19	1.27	1.52	0.87
	7	8			5.81	0.26	0.20	1.11	0.21	0.22	0.17	1.12	1.29	0.78
	8	9			12.52	0.27	0.20	1.06	0.10	0.08	0.13	0.50	0.50	0.52
	9	10			9.24	0.28	0.19	1.06	0.10	0.08	0.12	0.46	0.51	0.50
	10	11			6.01	0.28	0.19	1.05	0.08	0.07	0.12	0.40	0.45	0.46
	11	12			9.12	0.28	0.18	1.05	0.08	0.06	0.12	0.39	0.42	0.45
	12	13			18.25	0.28	0.18	1.04	0.12	0.74	0.77	0.54	0.74	0.65
	13	14	CLAY	< 0,65	100.00	0.28	0.18	1.04	0.09	4.00	4.00	0.42	2.00	2.00
	14	15			99.92	0.27	0.18	1.02	0.11	3.95	3.95	0.53	2.00	2.00

4. Discussion

From the comparison of the three methods, it is observed that the method proposed by Boulanger and Idriss (2014) yields FS values < 1 for materials with fines content (FC) greater than 30%, which are considered susceptible to liquefaction. In contrast, the Robertson (2009) method also produces FS values < 1 for materials with FC > 30%, while the method proposed by Moss et al. (2006) results in FS values > 1 for materials with FC < 30%. The determination of the estimated value of fines content (FC) is based on the equation proposed by Yi (2014).

In the method proposed by Robertson (2009), cyclic softening in clayey soils is considered in the liquefaction evaluation, although its contribution is relatively minor based on most available case history records. In contrast, the method by Moss et al. (2006) conducts the analysis by considering only cone resistance (qc) and friction ratio (Rf) as the primary variables to determine fines content (FC) and identify liquefaction-susceptible materials. Meanwhile, in the Boulanger and Idriss (2014) method, liquefaction potential within soil layers is evaluated by calculating the magnitude scaling factor (MSF), taking into account soil characteristics as well as soil density/strength.

In determining the cyclic stress ratio (CSR), all three methods employ the same fundamental equation, except in the calculation of the stress reduction factor (rd). Robertson (2009) determines rd by considering depth-dependent limits that influence the reduction factor. The method of Moss et al. (2006) calculates rd by incorporating earthquake magnitude, maximum horizontal acceleration, and depth. In contrast, Boulanger and Idriss (2014) determine rd using correction factors based on site response, which are evaluated as a function of soil layer depth.

With respect to the determination of the cyclic resistance ratio (CRR), the three methods differ significantly. Robertson (2009) determines CRR based on soil behavior type, while Moss et al. (2006) determine CRR using cone resistance (qt) and friction ratio (Rf) for each soil layer. Both Robertson (2009) and Moss et al. (2006) evaluate the duration effect of liquefaction triggering (MSF) primarily as a function of earthquake magnitude. In contrast, Boulanger and Idriss (2014) determine both CRR and MSF by considering the normalized clean sand cone resistance, $(qc_{1N})_{cs}$.

5. Conclusions

Based on the analysis of sediment characteristics using CPTu data, three types of sediment were identified in the study area are sand sediments ranging from sand to mixed sand, silt sediments ranging from sandy silt to clayey silt, and clay sediments consisting of clay.

The liquefaction potential in the study area indicates two conditions:

- FS < 1 (high) for saturated sand with very loose to loose density at all CPTu locations.
- FS = 1 (medium) for saturated sand with loose to medium density at all CPTu locations.

In general, the FS results from the three analyzed methods show similar outcomes, indicating liquefaction potential within saturated "clean sand" layers at depths ranging from approximately 4.5 to 15 meters below the surface.

The method most suitable for the study area is that of Boulanger and Idriss (2014). This is due to its use of a reduction factor calculated from site response based on soil layer depth, as well as its CRR formulation that incorporates clean sand penetration resistance— the dominant material in the study area and an important parameter controlling liquefaction susceptibility.

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